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FRACTURE DYNAMICS OF ROCK

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ABSTRACT

A concept of fracture dynamics of rock is introduced, three aspects of fracture being discussed, namely: stability of fracture propagation, terminal fracture velocity and dynamic stresses created by a propagating crack.

Work related to this new field of research is reviewed and theoretical and experimental studies on rock are reported. The practical significance of the fracture dynamics concept in rock mechanics is outlined.

INTRODUCTION

Intensive research, conducted mainly during the past few years, has resulted in considerable advances in the science of rock mechanics. Much progress has already been made towards achieving an understanding of rock fracture processes, knowledge of which is considered essential for the solution of practical rock mechanics problems in mining and in civil engineering.

While investigations related to fracture of rock have provided valuable information on various characteristics of this engineering material, considerable confusion has resulted from the ambiguous use of some terms in the literature on the subject. It is therefore necessary, to define clearly some of the terms which will be used in this paper.

FAILURE is a process by which a material changes from one state of behavior to another. The more important types of failure are yield, strength failure, fracture and rupture.

YIELD is the failure process by which a material changes from a state of predominantly elastic behavior to one of predominantly plastic behavior.

STRENGTH FAILURE is the failure process by which a material changes from a state in which its load–bearing capacity is either constant or increases with increasing deformation to a state in which its load–bearing capacity is decreased or has even vanished.

FRACTURE is the failure process by which new surfaces in the form of cracks are formed in a material or existing crack surfaces are extended. Various conditions and stages of fracture may be visualized, namely:–

Crack initiation is the failure process by which one or more cracks are formed in a material hitherto free from any cracks (Poncelet(1) concept).

Fracture initiation is the failure process by which one or more cracks pre–existing in a material start to extend (Griffith(2) concept).

Fracture propagation is the failure process by which cracks in a material are extending thus it is a stage subsequent to fracture initiation. It may be distinguished between two stages of fracture propagation, namely, stable and unstable.

Stable fracture propagation is the failure process of fracture propagation in which the crack extension is a function of loading and can be controlled accordingly.

Unstable fracture propagation is the failure process of fracture propagation in which the crack extension is also governed by other factors than the loading, e.g. crack velocity, thus becomes uncontrollable.

RUPTURE is the failure process by which a structure (e.g. a rock specimen) disintegrates into two or more pieces*.

Studies of rock fracture are broadly directed towards two aims, namely, to provide a phenomenological failure *criterion* and to provide a genetic failure *mechanism*, and it is important that a clear distinction be made between these two aspects. A failure criterion provides a formula to enable prediction of the strength values for all states of multiaxial stress in terms of a critical quantity obtained from a simple test such as the uniaxial tensile or compression test. A failure mechanism explains the sequence of events which occur in a material in the course of loading and eventually lead to failure. A failure criterion should be based upon knowledge of the failure mechanism but this is not always so. In fact, many failure criteria have been propounded on the basis of theoretical reasoning alone and have not so far been verified by experimental evidence. However, extensive investigations into the mechanism of brittle fracture of rock have recently been undertaken and a hypothesis has been advanced(3) describing the sequence of events taking place in rock from the initial application of load to the complete disintegration of material tested.

In Figure 1, axial stress versus lateral, volumetric and axial strain is plotted for quartzite tested in uniaxial compression. The characteristic events taking place in rock during loading are marked on these curves. The first stage of the process is *crack closure* when cracks inherent to any rock close under the applied compressive load. This is followed by linear elastic deformation leading to *fracture initiation* when closed cracks begin to enlarge. The stage of fracture initiation is indicated by departure from linearity for the lateral and volumetric strain–stress curves but not for the axial strain–stress curve. Fracture initiation is followed by stable fracture propagation leading to *critical energy release* which marks the onset of unstable fracture propagation manifested in the change of the curvature sign for the stress–volumetric strain curve and deviation from linearity for the axial strain–stress curve. During the process of unstable fracture propagation a characteristic transition takes place at the peak of the stress–axial strain curve when *strength failure* occurs. Strength failure represents the maximum stress, i.e. the strength of rock, and most rocks characterized by brittle fracture fail violently at this stage when tested in conventional (soft) loading machines. In such a case, the specimen–machine system becomes unstable and strength failure and rupture coincide. If, however, the stiffness of the testing machine is increased the fracture process will continue along the dotted line of the stress–axial strain curve in Figure 1. For very stiff loading machines (over 10 x 10^6 lb/in stiffness) a complete stress–strain curve of hard rock such as quartzite may be obtained with rupture occurring at zero stress. Rupture, therefore, is not a characteristic property of the rock *material but* depends on the stability of the rock *structure.* The fracture process of rock material is concluded when strength failure is reached, while the failure of the structure occurs when rupture is reached. Rupture therefore renders the structure useless while strength failure changes the material to one with decreasing load carrying capacity. This has important practical implications for the design of mining structures such as excavations whose shape and layout may be so chosen as to obtain stable structures which will not fail even if

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* Sometimes called by some authors 'final fracture' or 'ultimate failure'.

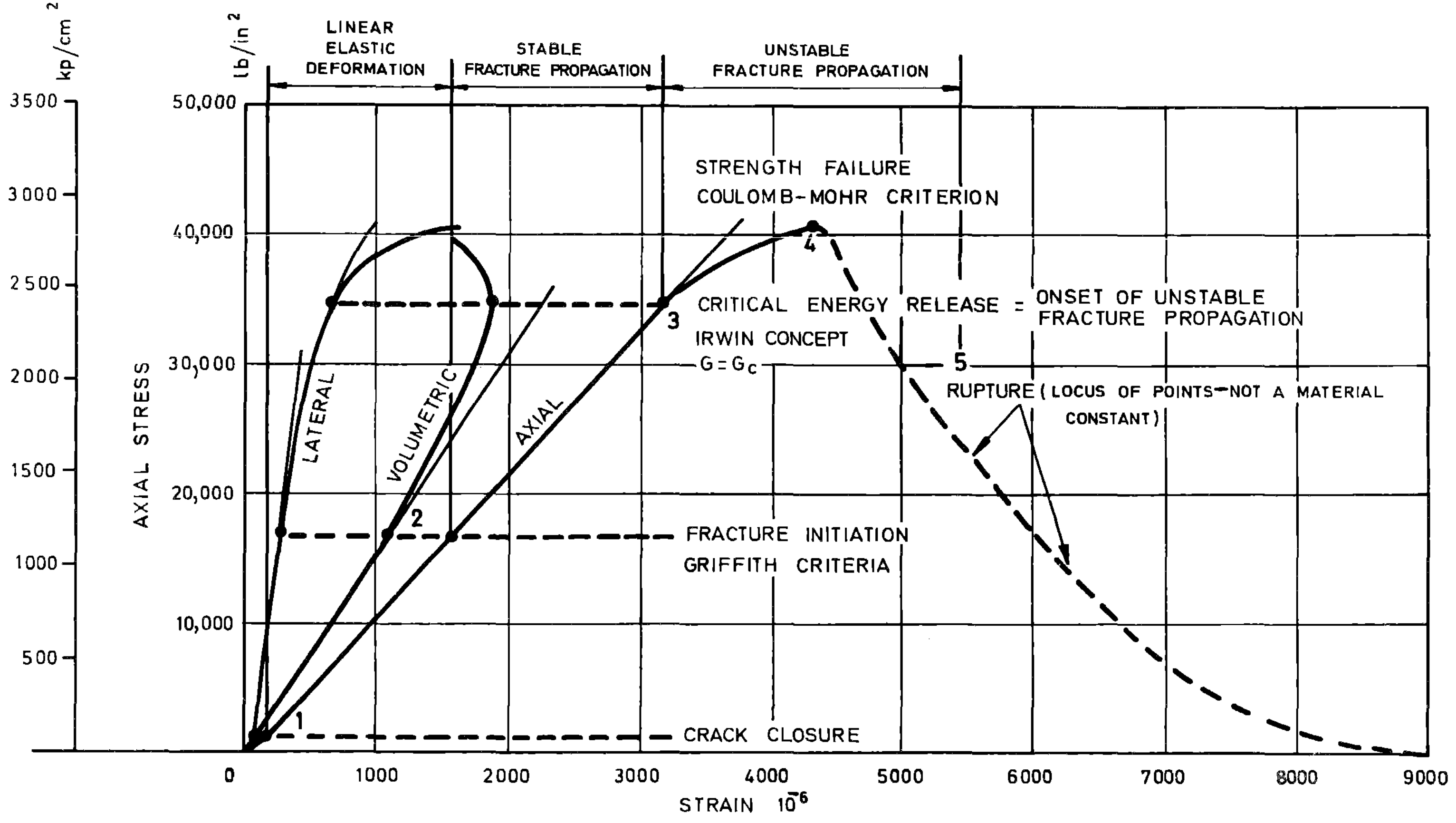


Figure 1 : Representation of brittle fracture processes in rock for quartzite tested in uniaxial compression.

the rock material surrounding such excavations has exceeded its strength, i.e. has suffered strength failure.

This mechanism of brittle rock fracture is equally applicable to uniaxial and triaxial compression as well as to multiaxial tension(3). In tension, however, the phenomenon of crack closure will, of course, be absent. In addition, under tensile stress conditions, fracture initiation, fracture propagation and rupture occur nearly simultaneously and, from a practical point of view, a fracture initiation criterion may be used to predict the tensile strength behavior of rock(3). As can be seen from Figure 1, such a procedure is no longer applicable in the case of failure occurring under compressive stress conditions due to the fact that fracture initiation, strength failure and rupture do not take place at the same stress level. This finding is particularly important because in the majority of practical rock mechanics problems, the predominant stress is usually compressive.

Having established the mechanism of brittle fracture of rock from experimental observations, failure criteria can now be considered for each stage of the rock fracture process. It should be stated in this respect that most research on fracture of rock has emphasized fracture *initiation* and very little work has been done on the subsequent stages of the rock fracture process. The extensively used Griffith theory(2) is now known to be applicable to rock fracture initiation only. Irwin's concept of critical energy release(4, 5) may be used to predict the onset of unstable fracture propagation while the well–known Coulomb–Mohr criterion is applicable to strength failure.

Due to the pre–occupation of previous research with fracture initiation, however, no acceptable failure criteria are as yet available for prediction of rock rupture – the most important stage of the fracture process from the point of view of applications to practical rock mechanics design problems.

It is thus clear that one of the most pressing areas of rock fracture research is an understanding of the fracture propagation process – and it is here that fracture dynamics of rock – the subject of the present paper – plays an important part.

Since fracture propagation studies in rock constitute one of the current research frontiers in rock mechanics, the related concept of fracture dynamics in rock needs some elaborating particularly since no previous publications are as yet available on this subject in rock mechanics literature.

It is known that mechanics – the study of the action of forces on bodies and of the motions they produce – has three branches namely statics, kinematics and dynamics. *Statics* deals with forces in equilibrium, *kinematics* deals with the theory of motion without reference to forces and *dynamics* is concerned with motions in its relation to forces and with the causes and effects of the motions. Some writers, however, use the term dynamics synonymously with mechanics, others restrict the term dynamics to both statics (balanced forces) and kinetics (unbalanced forces) and consider kinematics a branch of pure mathematics. Still others apply dynamics to what has been stated above as kinetics. It is clear therefore that some confusion exists.

In the present paper dynamics is defined as the study of the relations between motions and unbalanced forces. *Fracture dynamics* therefore is that branch of fracture mechanics which is concerned with the fracture phenomena associated with a propagating crack due to applied forces, that is, loading. Fracture dynamics includes fracture processes under gradually increasing loads (static stress conditions) as well as under shock or impact loads (dynamic stress conditions). It must therefore be emphasized that fracture dynamics is not merely fracture under dynamic stress conditions.

Fracture dynamics of rock will be dealt with under three headings, namely

(1) the stability of fracture propagation;

(2) the terminal fracture velocity;
(3) the dynamic stresses created by a propagating crack.

STABILITY OF FRACTURE PROPAGATION IN ROCK

Fracture propagation has been defined as the failure process by which cracks in a material are extending. The onset of fracture propagation may be determined by the well known Griffith energy balance(2) at fracture initiation on the basis of which the following relationship is derived:

$$\sigma = \sigma_{in} = \sqrt{2\gamma E/\pi c_o} \tag{1}$$

where σ is the applied uniaxial tensile stress;
σ_{in} is that value of σ when crack propagation initiates;
γ is the specific surface energy, i.e. the surface energy per unit length of the crack;
E is the modulus of elasticity; and
c_o is the half–length of the pre–existing (Griffith) crack.

The above condition implies that for

$$\sigma > [\sigma_{in} = \sqrt{2\gamma E/\pi c_o}] \tag{2}$$

fracture propagation will take place.

It has been defined(5) that fracture propagation is stable as long as there is a definite relationship between the half–length c of the propagating crack and the applied stress σ and the condition $\sigma > \sigma_{in}$ is maintained. It should be noted that σ and c are variables depending upon each other while σ_{in} and c_o are constants.

A relationship between σ and c for stable crack propagation has been proposed by Irwin(4) for brittle metals and applied to rock by Bieniawski(5). Irwin's relationship reads as follows:

$$\sigma = \sqrt{GE/\pi c} \tag{3}$$

where G is the energy released per unit crack surface area.

The above formula is based upon the concept that fracture propagation is due to the fact that a certain amount of energy, represented by G, is released from the stored energy of a structure and is used to form additional crack surface area. The energy is released at the same rate as energy is absorbed by the process of crack extension. G is not constant but depends upon the values σ and c at any instant.

It will be noted that, in essence, Irwin's formula takes the same appearance as (1), 2γ (constant) being replaced by G (not constant), but while (1) is a formula specifying a criterion, (3) constitutes a functional relationship between σ and c thus describing the law followed by stable fracture propagation.

It has also been postulated(5) that fracture propagation is unstable when the relationship between σ and c according to (3) ceases to exist, that is, when other quantities, e.g. the crack growth velocity, also play a role and fracture propagation Δc cannot be controlled any more by the applied stress changes $\Delta\sigma$. While, in stable propagation, the crack growth can be stopped by stopping load increases, this does not hold for unstable fracture propagation; the fracture then propagates uncontrollably although the stress may be kept constant.

Irwin has shown(4) that a criterion which determines transition from stable to unstable fracture propagation may be based on (3). He has propounded that fracture becomes unstable when the energy released per unit crack surface, G, attains a critical value, G_c, which is a characteristic property of the material.

Thus, fracture propagation becomes unstable when

$$\sigma = \sigma_u = \sqrt{G_c E/\pi c_u} \tag{4}$$

where σ_u is that value of the uniaxial applied stress when fracture propagation becomes unstable;
c_u is the corresponding crack half–length.

The value of G_c for a particular material may be determined by measuring the applied stress σ_u and the crack half–length c_u at the onset of unstable fracture propagation and making use of (4) as follows:

$$G_c = \frac{\pi \sigma_u{}^2 c_u}{E} \tag{5}$$

It should be noted that (1) and (5) were derived for plane stress conditions. The corresponding equation for G_c for plane strain conditions is

$$G_c = \frac{(1-\nu^2)\,\pi \sigma_u{}^2 c_u}{E} \tag{6}$$

where ν is Poisson's ratio.

Values of G_c have been determined for various materials and are listed in Table I. The Irwin concept of G_c has been verified experimentally by many workers in the field of fracture mechanics and is now used extensively in the design of such structures as pressure vessels, steam turbine–generator rotors, ships, aircraft, etc. This concept has also been applied by the author to rock and experimental determination of G_c for rock as well as its practical applications to mining are dealt with elsewhere(5).

The critical energy release, G_c, characterizes the transition from stable to unstable fracture propagation.

TABLE I

Critical energy release rate G_c for various materials

Material	G_c		Source
	lb–in/sq.in.	kp–cm/cm^2	
Glass	0.08	0.0143	Irwin
Concrete	0.11	0.0197	Kaplan
Quartzite	3.51	0.6283	Bieniawski
Norite	4.20	0.7518	Bieniawski
Ship steel	80.00	14.3200	Irwin
Aluminum	125.00	22.3750	Krafft
Rotor steel	135.00	24.1650	Winne & Wundt

TERMINAL FRACTURE VELOCITY OF ROCK

The importance of the fracture velocity in brittle fracture phenomena was first pointed out by Mott(6) in 1948. His studies, entirely theoretical, were concerned with the evaluation of the kinetic energy associated with the movement of the faces of a propagating crack. Mott indicated that if this kinetic energy were accounted for in the original Griffith energy balance the latter could lead to a valid fracture criterion.

The kinetic energy was determined by Mott for a crack in a plate subjected to uniformly distributed uniaxial tension, normal to the axis of the crack, and was given for plane stress conditions as:

$$W_k = k\rho c^2 v^2 \sigma^2 / 2E^2 \tag{7}$$

where W_k is the kinetic energy
k a proportionality factor
ρ the density of the material
c the crack half-length
v the crack velocity
σ the applied stress
E the modulus of elasticity.

Incorporating the above kinetic energy equation in the original Griffith energy balance, Dulaney and Brace(7) derived the expression for crack velocity which read as follows:

$$v = \sqrt{2\pi/k}\sqrt{E/\rho}\,(1 - v_o/c) \tag{8}$$

where c_o is the initial crack half-length, i.e. the length of the pre-existing (Griffith) crack.

It is obvious from (8) that crack velocity will, with increasing crack length, 2c, approach the asymptotic value

$$\sqrt{2\pi/k}\sqrt{E/\rho} = v_T \tag{9}$$

It will be noted from (9) that v_T, termed the terminal fracture velocity, is a characteristic property of the material. In fact, since $v_L = \sqrt{E/\rho}$ is the velocity of longitudinal wave propagation in a rod made of this material, the terminal fracture velocity is related to this wave propagation velocity.

Roberts and Wells(8) found that, by using the Westergaard solution for the stress field around a crack and assuming Poisson's ratio $\nu = 0.25$, one obtains:

$$v_T = 0.38\sqrt{E/\rho} \tag{10}$$

Using Roberts and Wells' analysis it may be shown that slightly higher values of $\sqrt{2\pi/k}$ are obtained for higher values of ν; in fact, $\sqrt{2\pi/k}$ varies approximately 5% about the value of 0.38 as ν varies 40% about the value of 0.25.

An expression for the terminal fracture velocity has also been derived by Poncelet(1) who showed that this velocity is one-half of the velocity of shear stress waves in the material, that is

$$v_T = 0.5\sqrt{S/\rho} \tag{11}$$

where S is the shear modulus of the material.

Stroh(9), in 1957, showed theoretically that the terminal fracture velocity coincides with the velocity of propagations of Rayleigh surface waves in a given material. Experimentally, however, the velocity of Rayleigh waves yields much higher values than those given by (10) and (11). This has been a puzzling problem for a number of years and it was only in 1964 that Broberg(10) showed that the Rayleigh velocity must be understood as the velocity in the strained medium as opposed to the previously considered Rayleigh velocity in the unstrained medium. This difference accounts for the discrepancy.

Experimental studies by Schardin(11) on glass, Van Elst(12) on steel and Bieniawski(13) on rock have confirmed that the terminal velocity is a phenomenon characteristic of brittle fracture. It was also found by Schardin that once the terminal fracture velocity is reached the phenomenon of crack forking (bifurcation or branching) takes place, that is, the propagating crack forms additional cracks at an angle to the original crack. This has been also subsequently observed in rock(13) – see Figure 2 – and it was further shown that the attainment of the terminal fracture velocity coincides with strength failure of the material.

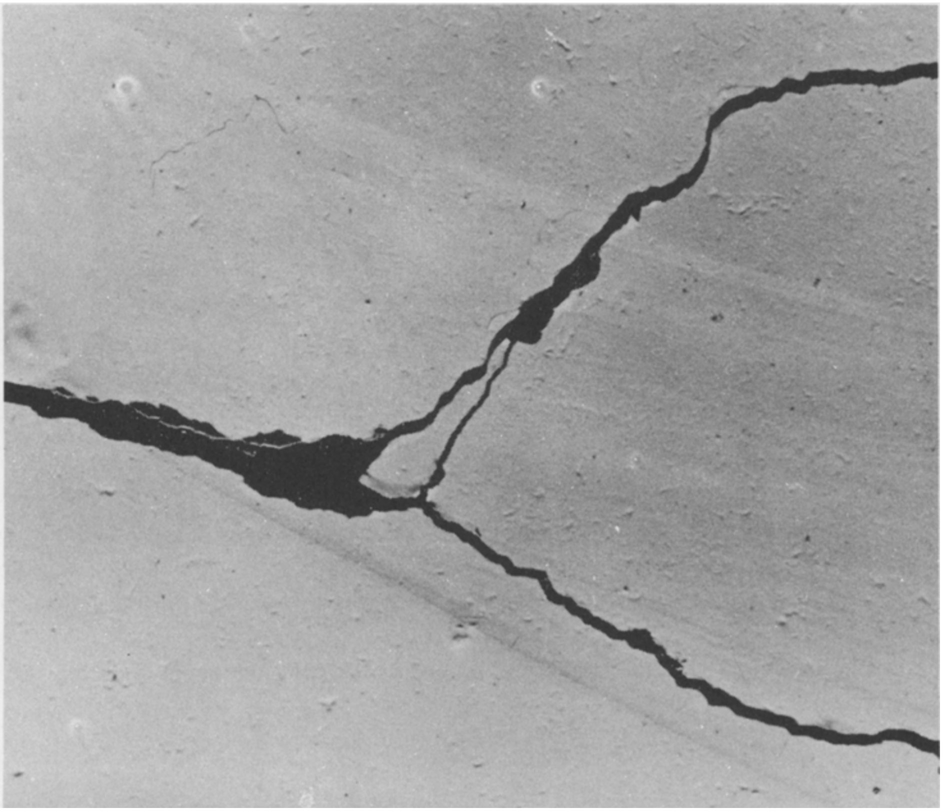


Figure 2: Crack forking in a plate of Norite rock occurring upon reaching the terminal fracture velocity of the propagating crack.

The complete velocity characteristics for a propagating crack have so far been determined experimentally by Schardin for glass(11) and by Bieniawski(13) for rock, in both cases using the techniques of ultra–high speed photography. In Figure 3 the experimental results obtained for norite are given. It may be noted from this figure that fracture propagation starts with low crack velocity. Furthermore Schardin(11) and Bieniawski(13) showed that up to the turning point of the curve, the elastic energy released by crack extension is not sufficient to maintain fracture. At a later stage, when the elastic energy released is able to maintain fracture, the crack velocity increases rapidly to a limit where it attains a constant value, namely, the terminal fracture velocity v_T. Consequently, the turning point of the curve, that is where $c/c_o = c_u/c_o$, $d^2v/dc^2 = 0$,

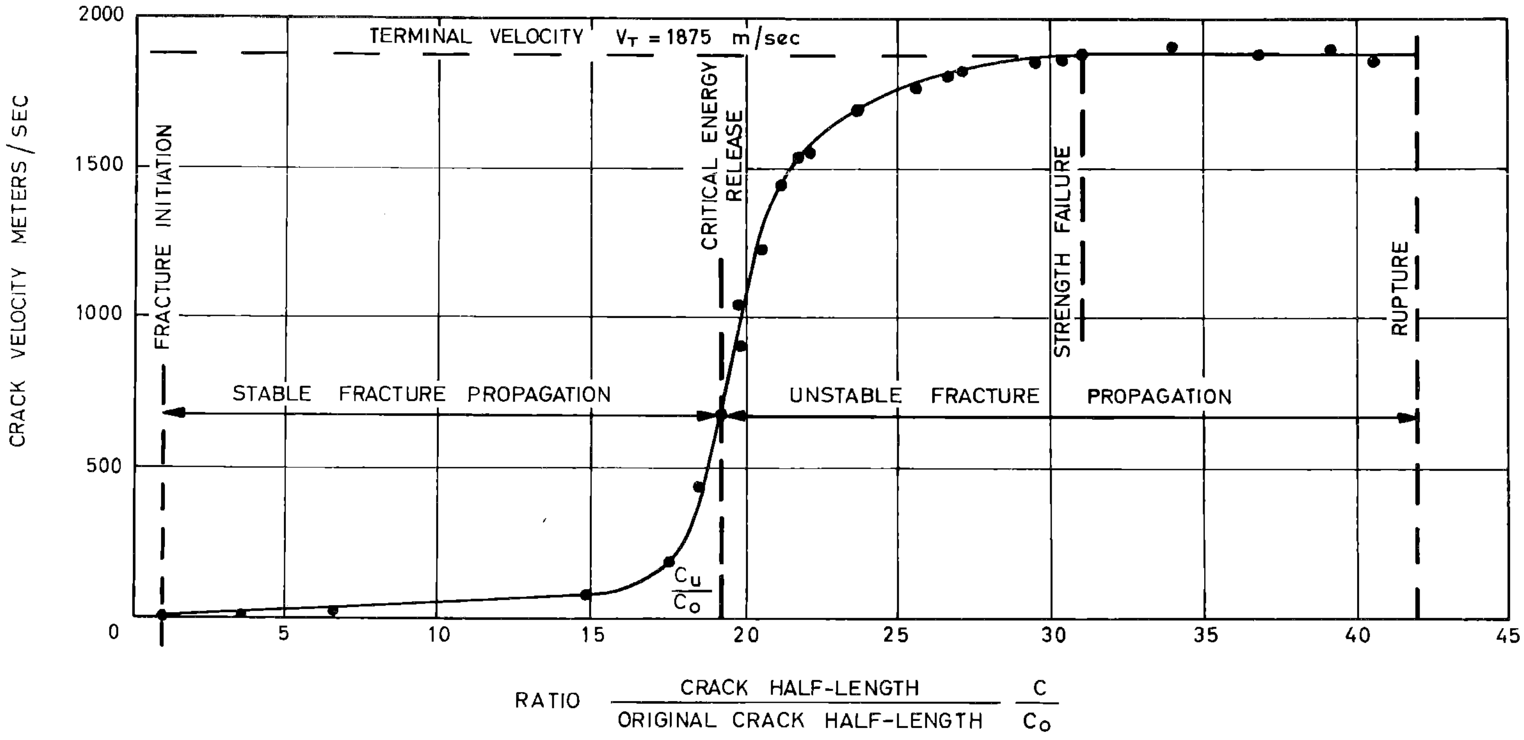


Figure 3: Fracture velocity data determined experimentally for norite.

marks the transition from stable to unstable fracture propagation, i.e. where $G = G_c$.

The actual relationship between the terminal fracture velocity and the velocities of the three types of elastic waves (longitudinal, shear and Rayleigh) has only recently been established by the author(13) for one material, that is, for a norite rock as given in Table II. The limited amount of experimental work that has been conducted on other materials such as glass, steel and some plastics was either concerned with the determination of terminal fracture velocity only or with measuring velocities of various elastic waves only.

TABLE II

Velocity data for norite

Velocity	Experimental values	Velocity ratios	
		Experimental	Theoretical
Terminal fracture velocity	v_T = 1875 m/sec	–	–
Velocity of longitudinal waves	v_L = 6480 m/sec	$\frac{v_T}{v_L} = 0.289$	$\frac{v_T}{v_L} = 0.38$
Velocity of shear waves	v_S = 3663 m/sec	$\frac{v_T}{v_S} = 0.512$	$\frac{v_T}{v_S} = 0.50$
Velocity of Rayleigh waves	v_R = 2759 m/sec	$\frac{v_T}{v_R} = 0.679$	$\frac{v_T}{v_R} = 1.00$

DYNAMIC STRESSES CREATED BY A PROPAGATING CRACK

Knowledge of the stress distribution surrounding a propagating crack is required for determining the ultimate stability of mining excavations and civil engineering rock structures. The dynamic stresses which are created by a propagating crack constitute therefore an integral part of fracture dynamics of rock.

In the study of brittle fracture in metals much attention has been given to the problem of dynamic stresses. The analyses conducted, although mainly theoretical, are equally applicable to rock and their major findings are thus worth mentioning here.

The theoretical treatises considered of particular interest to rock mechanics are those of Yoffe(14), Craggs(15) and Akita and Ikeda(16). The interested reader may also refer to papers by Baker(17), Williams(18), Irwin(19), Liu(20), Paris and Erdogan(21), Cotterell(22) and Barenblatt et al.(23) which also treat the subject but are of more academic interest to the rock mechanics engineer. On the experimental side much less information is available but of particular interest are works by Wells and Post(24), Carlsson(25), Flynn(26) and Akita and Ikeda(27). A detailed review of the above works was presented by the author elsewhere(28).

The above studies have shown that: –

1. As the crack velocity increases the stress required to maintain crack propagation decreases and from a certain velocity onwards the fracture propagation process will be self–maintaining. This critical velocity is the terminal fracture velocity v_T.
2. Crack forking occurs upon reaching the terminal fracture velocity.
3. The dynamic stress distribution around the propagating crack under static loading conditions differ negligibly from that under dynamic loading conditions.

The theoretically derived formulae describing the complete dynamic stress distribution at any point around a propagating crack in a given material are, however, extremely complicated, in many cases contradictory and in no instances known to the author verified by experimental evidence. This state of affairs presents considerable difficulties for the practical engineer and this is why experimental investigations are of considerable value. Although more expensive, experimental studies are often free of the many assumptions necessary to make theoretical solutions possible and, being more directly interpretable for practical applications, justify the expenditure involved. Pioneering work in this respect by Wells and Post(24) is particularly useful and their general approach, namely of making use of photoelasticity has been adopted by the South African Council for Scientific and Industrial Research.

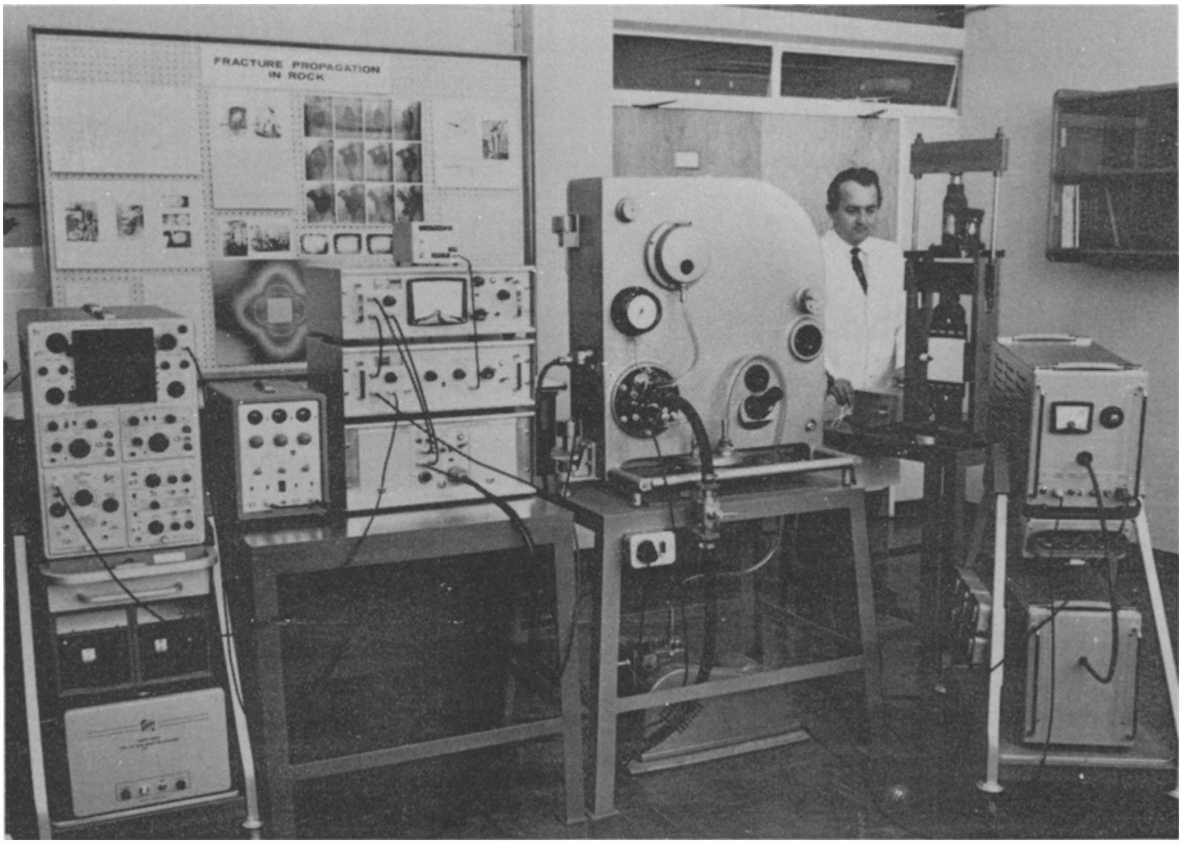
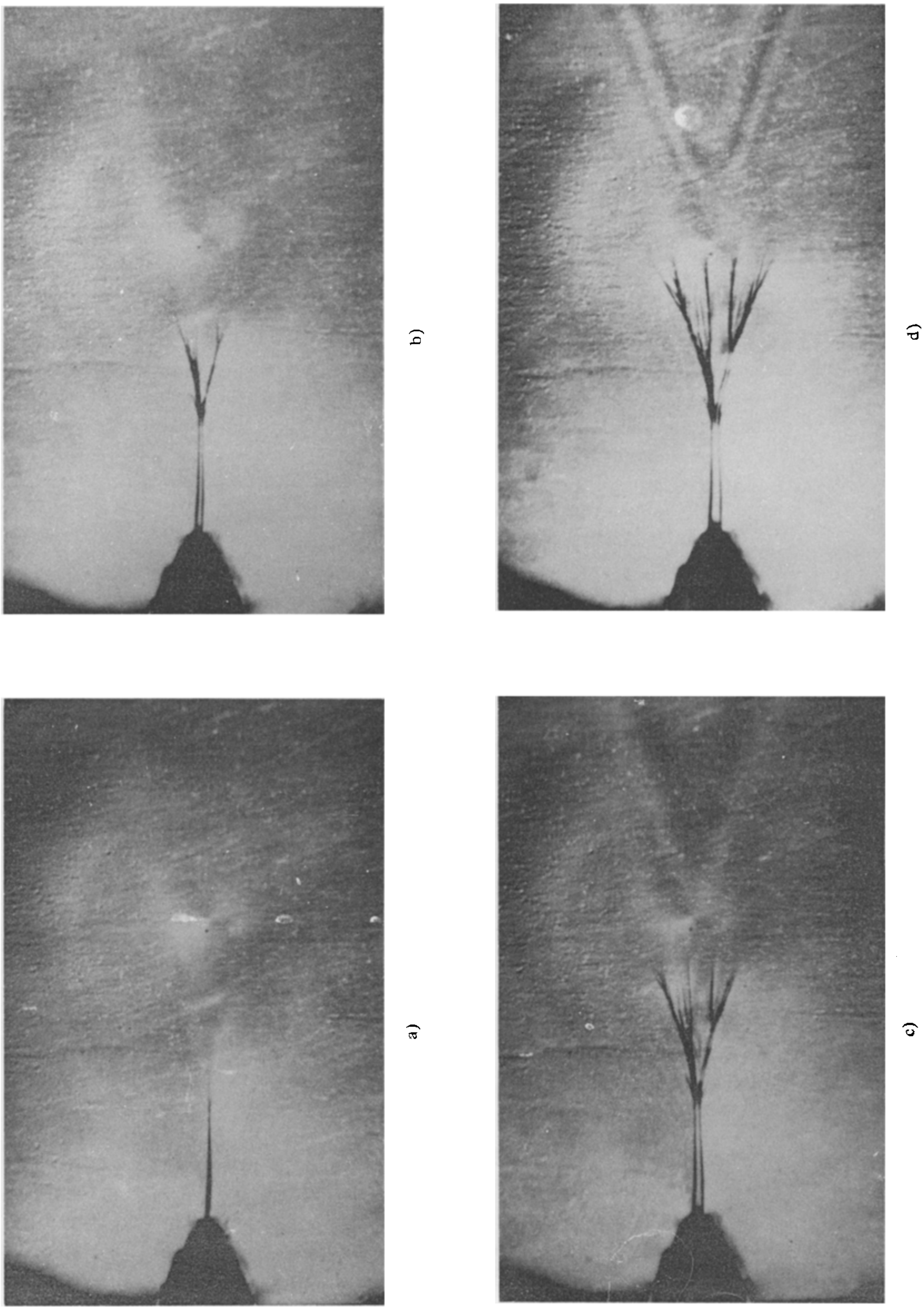


Figure 4: An ultra–high speed camera system used for fracture dynamics studies on rock.

Studies of dynamic stress distributions of the propagating rock fracture are conducted employing an ultra high–speed framing camera system, illustrated in Figure 4 and capable of maximum speeds of 1.6 million frames per second. Use is made of either pure photoelasticity or of birefringent coating technique, the typical results of these studies being shown in Figures 5 and 6. As these investigations represent a research field on their own they will be made the subject of a separate publication by the author.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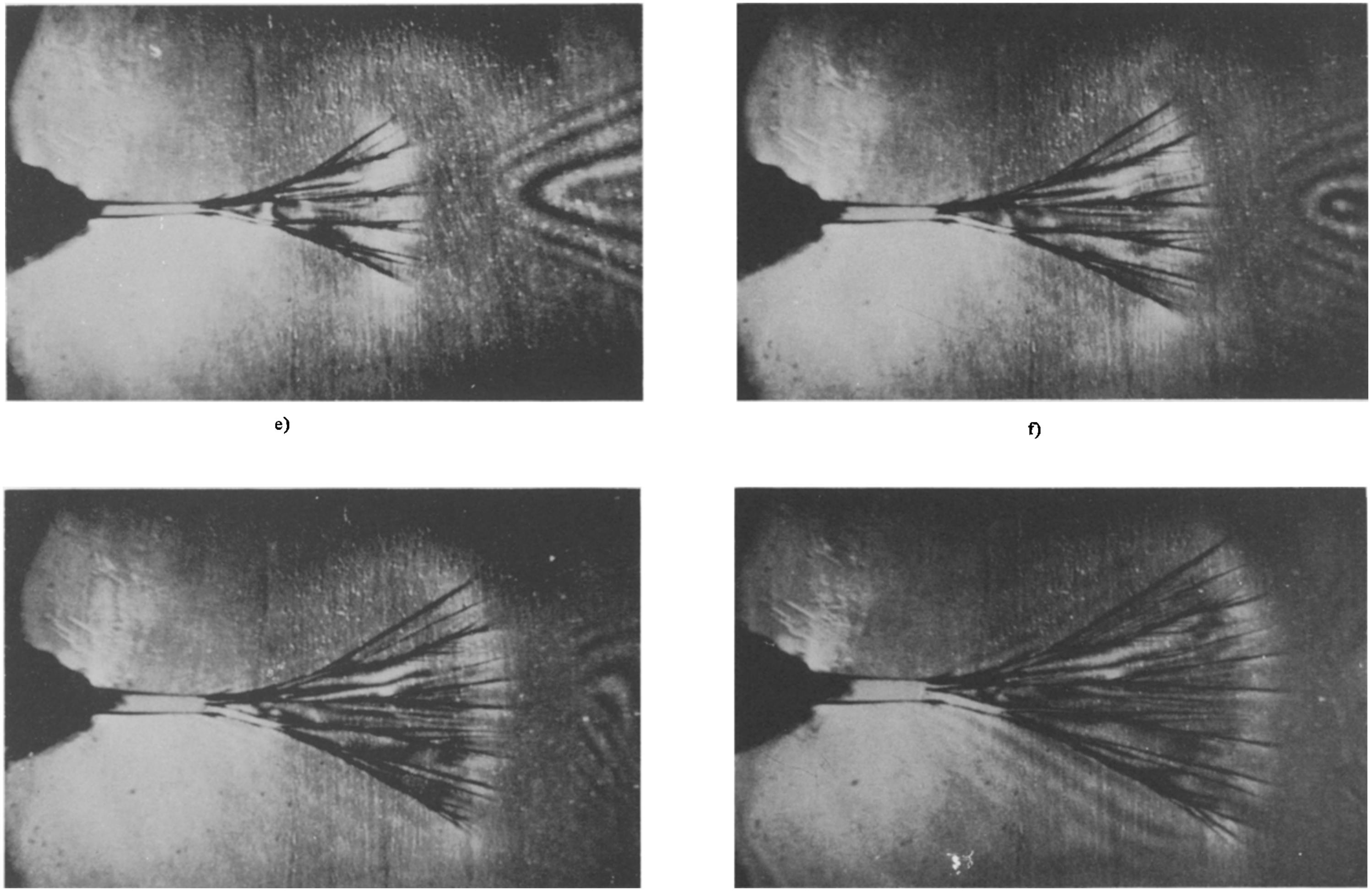

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Figure 5: Photographic record of fracture propagation obtained by the ultra–high speed camera at 1.5 million frames per second.

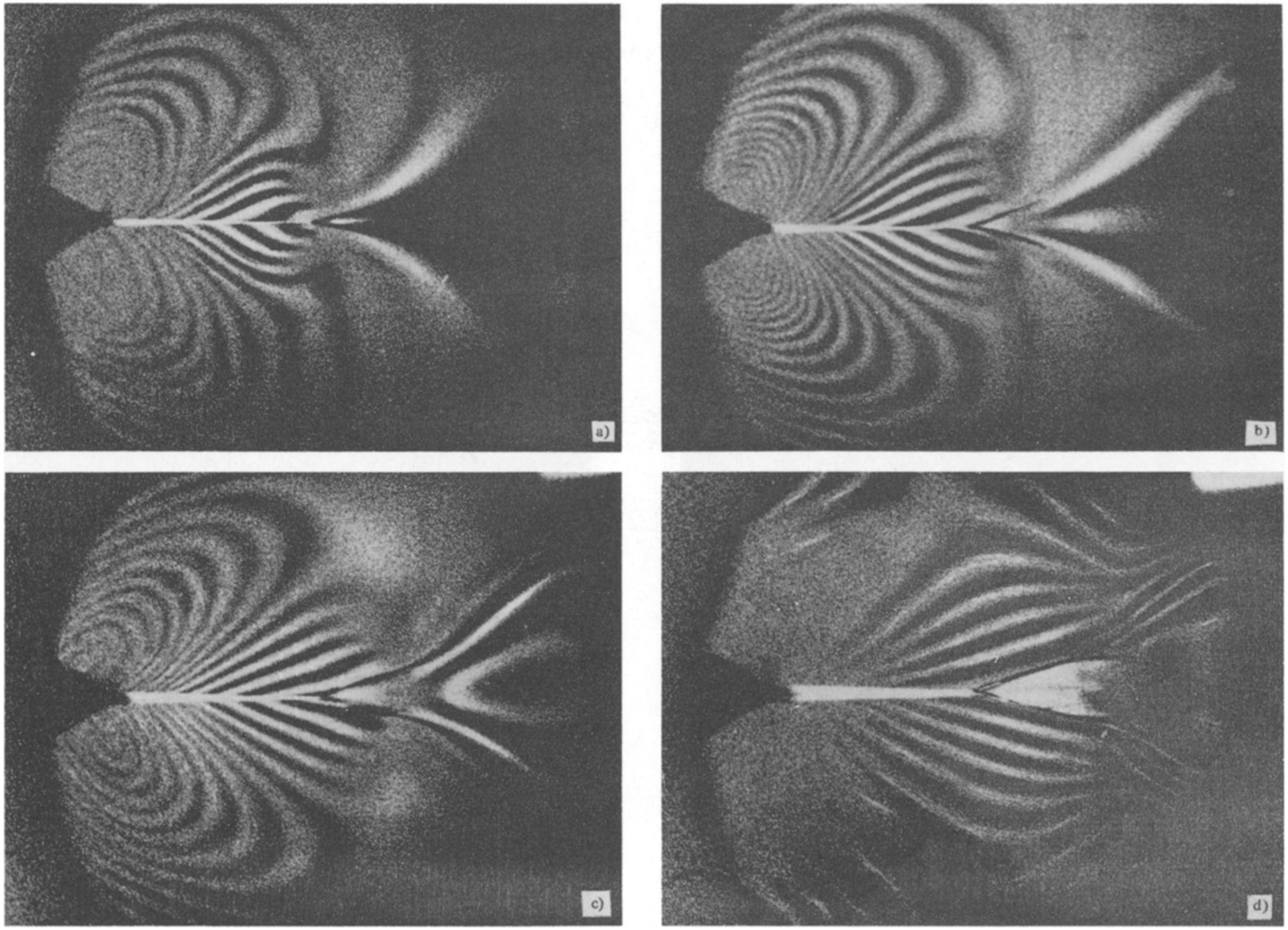

Figure 6: A sequence of photographs showing successive changes in dynamic stress distribution associated with a propagating crack (500,000 frames per second).

PRACTICAL SIGNIFICANCE OF FRACTURE DYNAMICS IN ROCK MECHANICS

The science of rock mechanics is the source of knowledge for the practical mining and civil engineer, in the solution of problems involving the strength and stability of rock structures.

It will be appreciated from the foregoing that fracture dynamics constitutes the key to an understanding of fracture propagation processes in rock and should lead to the safe and economical design of structures in this material.

The following areas of practical application are envisaged:

1. Determination of the stability of a structure in rock.
2. Amelioration of such hazards as rockbursts by determining the velocity with which fracture propagates in rock and thus allowing for necessary precautions to be made in time.
3. Determination of dynamic stresses in a structure under a stress system thus ensuring safe and economic shape and layout of excavations in rock.
4. Improving the efficiency of rock breaking operations such as drilling and blasting through providing the data on fracture propagation characteristics of rock.
5. Provision of valid failure criteria for the prevention or promotion of rock fracture.

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RÉSUMÉ – L'idée de la dynamique de rupture dans la roche est introduite; trois aspects des ruptures sont examinés, à savoir: la stabilité de la propagation de la rupture, la vitesse finale de la rupture, et les contraintes dynamiques créées par une rupture qui est propagé.

Un compte–rendu est fait sur les travaux executés dans ce domaine nouveau de recherche, et les études théoriques et les expériences pratiques sont passées en revue. L'importance pratique de l'idée de la dynamique de la rupture dans le domaine de la mécanique des roches est donnée.

ZUSAMMENFASSUNG – Der Begriff der Bruchdynamik von Gesteinen wird eingeführt, wobei drei Erscheinungen des Bruchvorganges diskutiert werden, und zwar: Stabilität der Bruchfortpflanzung, Grenzgeschwindigkeit der Bruchfortpflanzung und dynamische Spannungen, die durch einen sich fortpflanzenden Bruch erzeugt werden.

Die für dieses neue Forschungsgebied einschlägige Literatur wird besprochen und theoretische und experimentelle Untersuchungen an Gestein werden dargelegt. Die praktische Bedeutung des Begriffes der Bruchdynamik für die Gebirgsmechanik wird erlautert.